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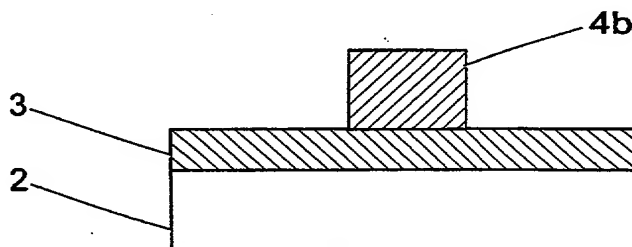
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**US 5563979 A**      **US 5416884 A**      **US 4988156 A**  
**US 4929302 A**

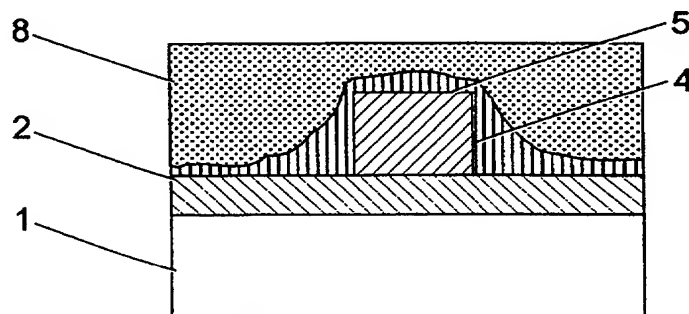
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UK CL (Edition R ) **G2J JGDA**  
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(54) Abstract Title  
**Multi-core waveguide**

(57) An optical waveguide with a multi-layer core (6) comprises a substrate (2), a composite core waveguide (7) formed on the substrate (2) and at least one upper cladding layer (8) embedding said core waveguide (7). The core waveguide (7) is characterised by a composite core layer (6) comprising a first core layer (4) with a consolidation temperature  $T_{1C}$  formed on the substrate (2) and an other core layer (5) formed on the first core layer (4), wherein the softening temperature  $T_{2S}$  of at least one of said an other core layer (5) is equal to or less than the consolidation temperature  $T_{1C}$  of underlying core layer (4). Preferably, both core layers are applied and then heated to above  $T_{1C}$ .

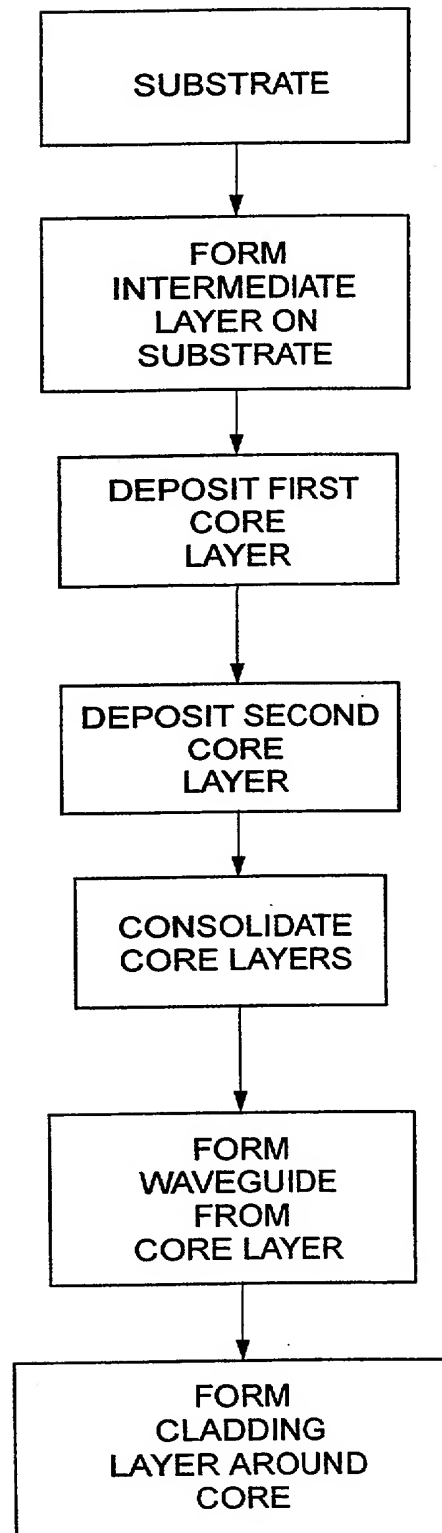


*Fig. 2C*



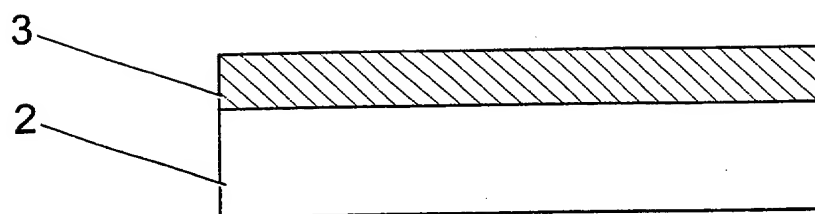
*Fig. 2D*

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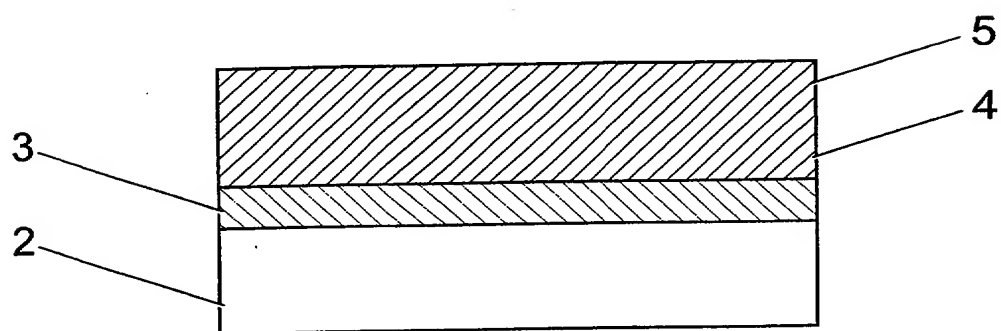


*Fig. 1*

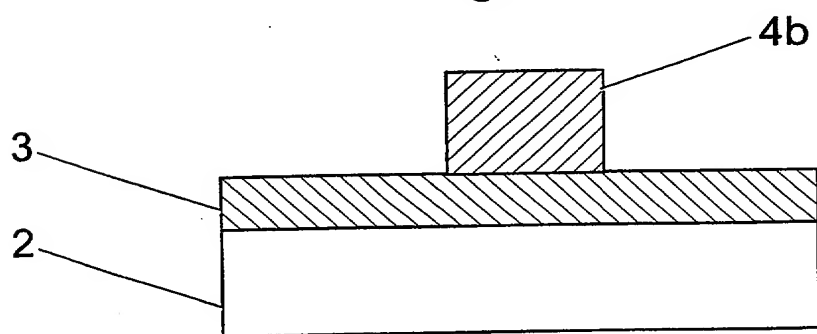
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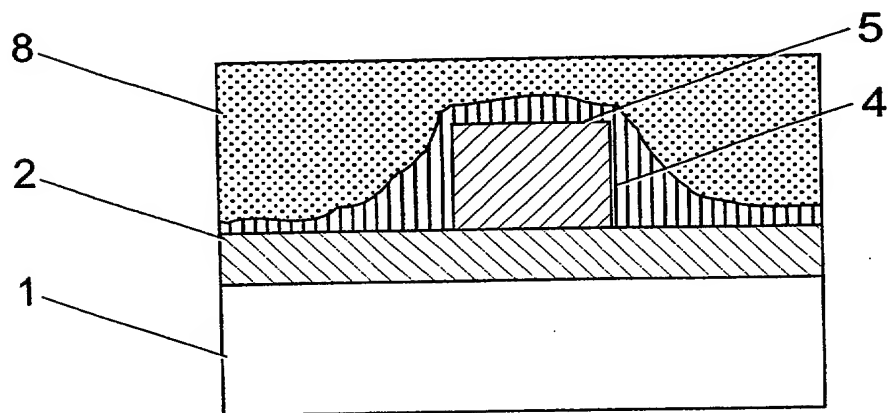
*Fig. 2A*



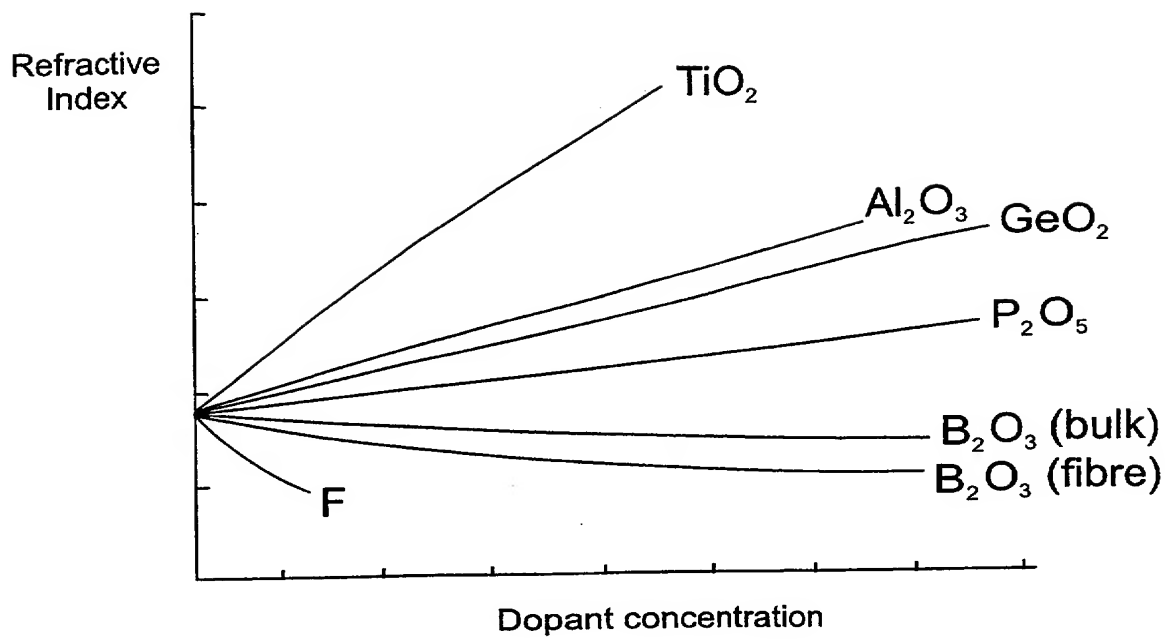
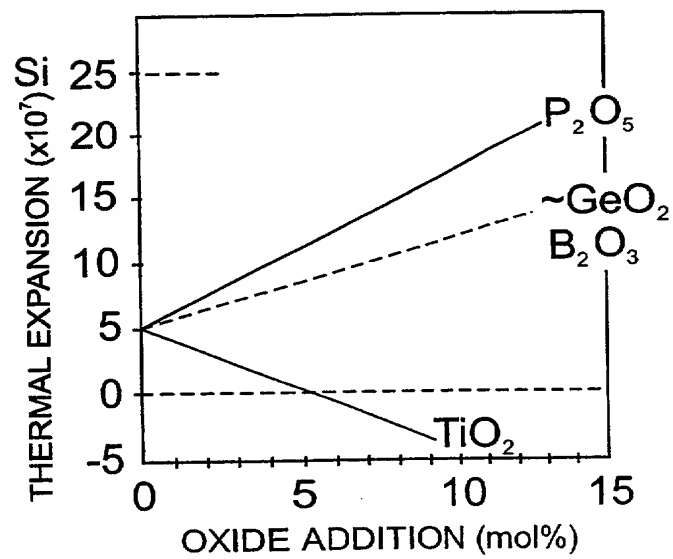
*Fig. 2B*

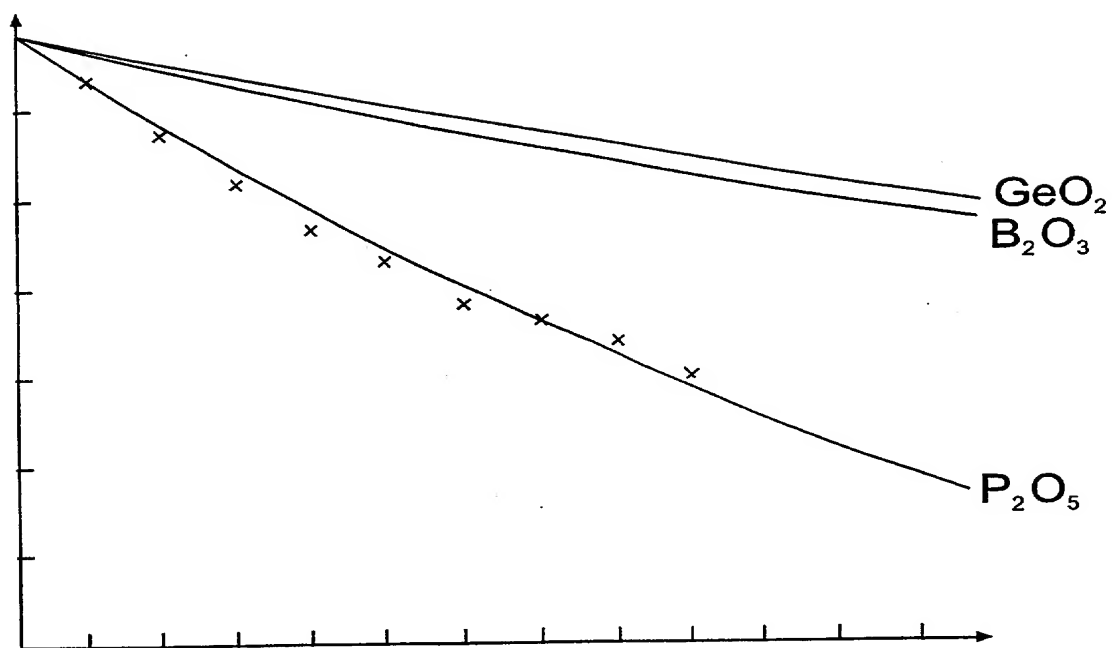


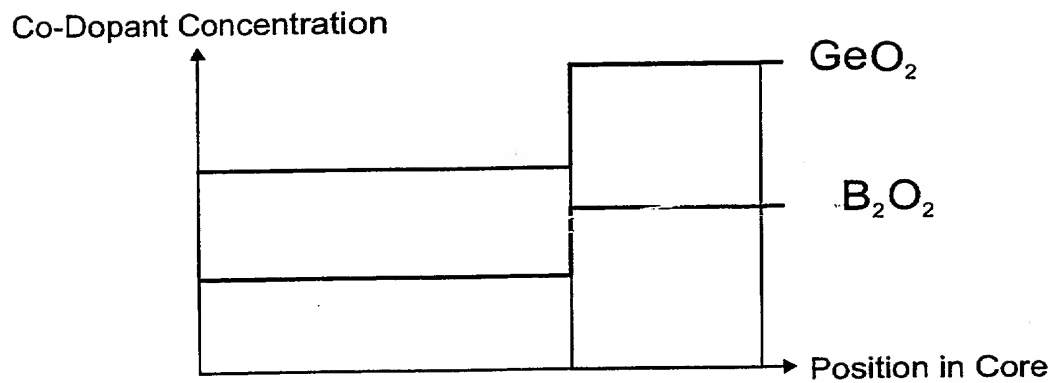
*Fig. 2C*



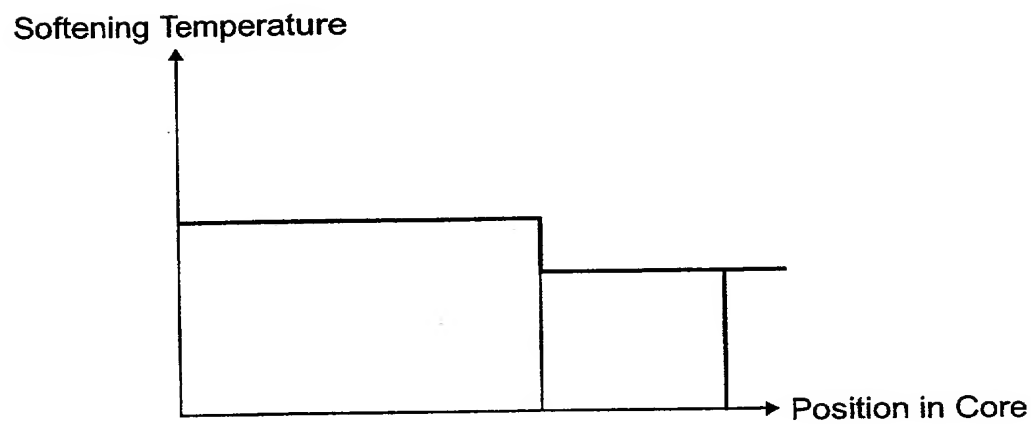
*Fig. 2D*

*Fig. 3**Fig. 4*

*Fig. 5*



*Fig. 6A*



*Fig. 6B*

1 OPTICAL WAVEGUIDE WITH A MULTI-LAYER CORE AND METHOD OF  
2 FABRICATION THEREOF

3  
4 This invention relates to an optical waveguide with a  
5 multi-layer core and in particular to an optical  
6 waveguide with a composite core in which the  
7 consolidation temperature of a first core layer is  
8 above the softening temperature of a second core layer  
9 deposited thereon.

10  
11 Planar waveguides are fabricated by forming several  
12 layers on top of a substrate, usually a silicon wafer.  
13 In the case of a FHD fabrication process, the layers  
14 which make up the waveguide are first deposited as a  
15 layer of fine glass particles or "soot". Alternatively  
16 the glass can be deposited by a variety of other  
17 techniques, for example, plasma enhanced chemical  
18 vapour deposition (PECVD), low pressure chemical vapour  
19 deposition (LPCVD), which may be done in isolation or  
20 combination and further may be in combination with  
21 flame hydrolysis deposition (FHD).

22  
23 In the case of the FHD process the soot layers are  
24 consolidated into denser glass layers, either  
25 individually immediately after each layer is deposited  
26 or several layers may be consolidated together. In the

1 case of the other processes, although deposited as a  
2 glass a densification and/or desiccation procedure is  
3 often also employed. If a layer is heated to a  
4 sufficiently high temperature in excess of its  
5 consolidation temperature, the viscosity of the  
6 consolidated layer is reduced until eventually the  
7 glass is able to flow. When this occurs, surface  
8 irregularities can be removed as the surface of the  
9 layer is smoothed.

10

11 During fabrication of an optical planar waveguide, it  
12 is known to consolidate a core layer using a  
13 temperature cycle in which at one stage the layer is  
14 heated to the "softening" temperature, which is  
15 significantly higher than the actual consolidation  
16 temperature. This enhanced temperature stage ensures  
17 that the glass forming the core layer is sufficiently  
18 softened at its top surface for the consolidated core  
19 layer to flow and form a relatively smooth and level  
20 layer.

21

22 The smoother the surface of a waveguide the less light  
23 is scattered at the surface; heating a layer to its  
24 softening temperature for a period of time is therefore  
25 desirable if a high-quality waveguide is to be  
26 fabricated. However, to ensure that the underlying  
27 layers are not deformed during the consolidation and/or  
28 softening of subsequent layers, the consolidation and  
29 softening temperatures of each subsequent layer are  
30 usually less than the softening temperature of the  
31 underlying layer.

32

33 In order to achieve a suitably smooth core layer upper  
34 surface, without reaching temperatures which exceed the  
35 consolidation temperatures of the underlying layers  
36 and/or which could cause thermal deformation of the

1 waveguide's substrate, it is usually desirable to  
2 introduce selected dopants into the core layer during  
3 the deposition stage.

4  
5 The composition of the glass forming the lowest core  
6 layer is thus selected so that its refractive index is  
7 close to that of the overlying core layer(s) whilst its  
8 consolidation temperature is greater than the softening  
9 temperature of the temperature of the topmost overlying  
10 core layer. Similarly, the cladding formed around the  
11 core layers and under the core layers must have the  
12 correct thermal characteristics to ensure that the core  
13 is not deformed during fabrication of the waveguide.

14  
15 As a consequence all layers (buffer if employed, core  
16 and cladding) must be deposited with decreasing  
17 consolidation temperature and sufficient buffer in  
18 between each. In addition, the maximum consolidation  
19 temperature allowed, typically for the core layer, is  
20 limited to ~1360°C by the onset of striations and  
21 implosions due to the silicon substrate.

22  
23 The selected core dopants lower the temperature at  
24 which the top surface of the core layer begins to flow.  
25 For example, dopants such as boron, phosphorous and/or  
26 titanium ion species may be introduced into germano  
27 silicate glass during the deposition stage in selected  
28 quantities to give the desired properties, for example,  
29 the right thermal characteristics, refractive index and  
30 coefficient of expansion. Other co-dopants could  
31 include tantalum, aluminium, lanthanum, niobium and  
32 zirconium. Germano silica based core glass is the  
33 preferred example but germania may not be necessary in  
34 all cases.

35  
36 The invention seeks to provide several advantages in

1 the fabrication of an optical waveguide. The waveguide  
2 according to the invention has a composite core in  
3 which a first layer comprises a glass whose  
4 consolidation temperature is close to the maximum  
5 allowed ( $\sim 1360^{\circ}\text{C}$ ). A "skinning" layer is then  
6 deposited on top of the underlying core layer(s) whose  
7 thickness is only of the order of ten percent of the  
8 thickness of the underlying core layer(s). Generally,  
9 the "skinning" layer has a much increased dopant  
10 concentration but match the refractive index of the  
11 underlying core layer(s). This uppermost "skinning"  
12 layer typically has a consolidation temperature  $\sim 50^{\circ}\text{C}$   
13 less than the consolidation temperature(s) of the  
14 underlying core layer(s). The uppermost "skinning"  
15 layer fully consolidates and, due to its softening  
16 temperature being lower than the consolidation  
17 temperature(s) of the underlying core layer(s), is  
18 further softened. This promotes a surface "skinning  
19 effect" which gives rise to a low surface roughness.  
20 The region of increased dopant is thus minimised, and  
21 is located, for example, at the edge of the waveguide  
22 core where the optical field of the guided mode is  
23 minimised: the impact of any density fluctuations is  
24 thus reduced.

25  
26 In order to ensure that both the consolidation and the  
27 softening temperatures of the core layer are  
28 sufficiently low, the core layer needs to be quite  
29 heavily doped. At such high levels of concentration,  
30 the dopants are more susceptible to non-uniform  
31 distribution within the core layer, and this results in  
32 the core layer exhibiting an undesirably high level of  
33 density fluctuations. The presence of density  
34 fluctuations affects the consistency of the refractive  
35 index across the layer, which should be as uniform as  
36 possible if the waveguide is to be used in large scale

1 applications, for example, such as an array waveguide  
2 grating. The minimisation of such density fluctuations  
3 is particularly desirable in the fabrication of large-  
4 scale waveguides, for example, waveguides whose  
5 dimensions are in excess of  $2 \times 2 \mu\text{m}^2$ .

6  
7 Furthermore, when cladding the core, since the volume of  
8 the softer core glass is minimised a closer match in  
9 consolidation temperature between the clad and core  
10 layers can be employed before significant deformation of  
11 the core layer is observed.

12  
13 During the consolidation phase, there is a reduction in  
14 surface area whilst at the same time an increase in  
15 density of the deposited layer. Necking between the  
16 deposited soot particles forms an open network with  
17 pores, which subsequently densifies with closure of the  
18 pores. Thus, it is essential that the consolidation  
19 conditions employed ensure that the lower viscosity  
20 uppermost (or "skinning" layer) does not consolidate  
21 prematurely.

22  
23 Poor consolidation conditions may give rise to gas  
24 trapping problems which would damage the consolidating  
25 layer(s). To mitigate this, a suitable consolidation  
26 ramp temperature rate, such as for example  $5^\circ\text{C}/\text{min}$ , may  
27 be used which enables the consolidating layer to be  
28 formed bubble free. He gas can also be used as it aids  
29 sintering by promoting core collapse.

30  
31 The present invention seeks to obviate or mitigate the  
32 aforementioned disadvantages by providing a waveguide  
33 with a multi-layer core which has a uniform refractive  
34 index and a smooth uppermost surface.

35  
36 A first aspect of the invention seeks to provide an  
37 optical waveguide with a multi-layer waveguide core, the

1 waveguide comprising:  
2 a substrate;  
3 a waveguide core formed on the substrate; and  
4 at least one upper cladding layer embedding said  
5 waveguide core, the waveguide core having a composite  
6 core layer comprising:  
7 a first core layer with a softening temperature  $T_{1s}$   
8 formed on the substrate; and  
9 at least one other core layer formed on the first  
10 core layer, wherein the softening temperature  $T_{2s}$  of at  
11 least one of said at least one other core layers is less  
12 than the softening temperature  $T_{1s}$  of an underlying core  
13 layer.  
14  
15 Preferably, the softening temperature  $T_{2s}$  of at least one  
16 of said at least one other core layers is at least  $10^{\circ}\text{C}$   
17 less than the softening temperature  $T_{1s}$  of at least one  
18 underlying core layer.  
19  
20 Preferably, the softening temperature  $T_{2s}$  of at least one  
21 of said at least one other core layers is substantially  
22 equal to or less than a consolidation temperature  $T_{1c}$  of  
23 at least one underlying core layer.  
24  
25 Preferably, said substrate is silicon.  
26  
27 Preferably, said substrate further comprises at least  
28 one buffer layer formed thereon.  
29  
30 Preferably, at least one said buffer layer is a  
31 thermally oxidised layer of the substrate.  
32  
33 Preferably, at least one layer of said: first core  
34 layer, said at least one other core layer, and/or said  
35 at least one upper cladding layer comprises silica  
36 and/or germanium oxide.  
37

1 More preferably, at least one of said first core layer,  
2 said at least one other core layer, and/or said at least  
3 one upper cladding layer is doped with at least one ion  
4 species taken from the group consisting of:

5       phosphorus, boron, titanium, tantalum, aluminium,  
6 lanthanum, niobium, zirconium and/or any other  
7 transition element.

8  
9 More preferably, said at least one silica and/or  
10 germanium oxide layer is doped with at least one species  
11 taken from the group consisting of:

12       a transition element, a rare earth ion species  
13 and/or a heavy metal ion species.

14  
15 Preferably, the thickness of first core layer is greater  
16 than the thickness of said at least one other core  
17 layer.

18  
19 More preferably, the thickness of the first core layer  
20 is the major portion of the thickness of the composite  
21 core layer.

22  
23 According to a second aspect of the invention, there is  
24 provided a method of fabricating an optical waveguide  
25 with a waveguide core comprising the steps of:

26       forming a substrate;  
27       forming a composite core layer on said substrate;  
28       forming a waveguide core from said composite core  
29 layer; and

30       forming at least one upper-cladding layer to embed  
31 said core waveguide, wherein the formation of the  
32 composite core layer is characterised by:

33       forming a first core layer with a softening  
34 temperature  $T_{1s}$  on the substrate; and

35       forming at least one other core layer on the first  
36 core layer, wherein the softening temperature  $T_{2s}$  of at  
37 least one of said at least one other core layer is

1 substantially less than the softening temperature  $T_{1s}$  of  
2 at least one underlying core layer.

3

4 Preferably, the softening temperature  $T_{2s}$  of at least one  
5 of said at least one other core layer is at least  $10^{\circ}\text{C}$   
6 less than the softening temperature  $T_{1s}$  of at least one  
7 underlying core layer.

8

9 More preferably, the softening temperature  $T_{2s}$  of at  
10 least one of said at least one other core layer is  
11 substantially equal to or less than a consolidation  
12 temperature  $T_{1c}$  of at least one underlying core layer.

13

14 Preferably, at the softening temperature  $T_{2s}$  of the said  
15 at least one other core layer, the viscosity of the said  
16 at least one other core layer is sufficiently reduced to  
17 lessen surface irregularities in said at least one other  
18 core layer.

19

20 Preferably, said step of forming a substrate includes  
21 the formation of at least one buffer layer on said  
22 substrate.

23

24 Preferably, the formation of at least one of: said at  
25 least buffer layer, said first core layer, said at least  
26 one other core layer, and said upper cladding layer  
27 comprises the steps of:

28        depositing a soot layer of fine particulate  
29 material;

30        consolidating said deposited soot layer.

31

32 Preferably, said soot deposition is by a flame  
33 hydrolysis deposition process, and/or any other planar  
34 soot deposition technique or combination of soot  
35 depositing techniques and non-soot depositing  
36 techniques.

37

1 More preferably, said consolidation is by heating with a  
2 flame hydrolysis burner and/or in a furnace.

3

4 Preferably, the formation of at least one of: said at  
5 least buffer layer, said first core layer, said at least  
6 one other core layer, and said upper cladding layer  
7 comprises the steps of:

8 depositing said layers of material by means of a  
9 plasma enhanced chemical vapour deposition process, a  
10 low pressure chemical vapour deposition process and/or  
11 any other planar deposition technique or combination of  
12 deposition techniques;

13 subjecting the deposited layer to a temperature  
14 controlled environment such that said deposited layer is  
15 sintered.

16

17 Preferably, the composition of at least one layer of  
18 said: first core layer, at least one other core layer,  
19 and/or said at least one upper cladding layer includes  
20 silica and/or germanium oxide.

21

22 More preferably, at least one layer of said: first core  
23 layer, said at least one other core layer, and/or said  
24 at least one upper cladding layer is doped with at least  
25 one ion species taken from the group consisting of:

26 phosphorus, boron, titanium, tantalum, aluminium,  
27 lanthanum, niobium, zirconium and/or any other  
28 transition element.

29

30 Preferably, at least one silica and/or germanium oxide  
31 layer is doped at least one ion species taken from the  
32 group consisting of:

33 a transition element, a rare earth ion species  
34 and/or a heavy metal ion species.

35

36 Preferably, the quantities of dopant are selected to  
37 form a waveguide with a refractive index difference of

1 between 0.2-2% with respect to the buffer.

2  
3 The lower core layer may be  $\text{SiO}_2$  co-doped with a  
4 Germanium and/or Boron and/or Phosphorus ion species.  
5 The upper core may be  $\text{SiO}_2$  co-doped with a Germanium  
6 and/or a Boron and/or a Phosphorus ion species.

7  
8 Preferably, the softening temperature ( $T_{2s}$ ) of the said  
9 at least one other core layer is at least  $10^\circ\text{C}$  less than  
10 the consolidating temperature ( $T_{1c}$ ) of said first core  
11 layer.

12  
13 The consolidation temperature ( $T_{1c}$ ) of said first core  
14 layer may be in the range  $1200^\circ\text{C}$ - $1375^\circ\text{C}$ .

15  
16 Preferably, the consolidation temperature  $T_{2c}$  of the  
17 second core layer is between  $1100^\circ\text{C}$  to  $1365^\circ\text{C}$ .

18  
19 Preferably, the composition and concentration of dopants  
20 in any one lower layer and/or substrate is selected to  
21 control the degree of softness exhibited by any  
22 overlying layer at a predetermined temperature.

23  
24 Preferably, during the consolidation, the temperature  
25 conditions include a stage where the temperature  
26 gradient rises at  $15^\circ\text{C min}^{-1}$  between  $650^\circ\text{C}$  to  $850^\circ\text{C}$ .

27  
28 Preferably, during the consolidation, the temperature  
29 conditions include a stage where the temperature  
30 gradient rises at  $5^\circ\text{C min}^{-1}$  between  $850^\circ\text{C}$  to  $1375^\circ\text{C}$ , and  
31 the dopant concentrations are selectively controlled so  
32 that thermal deformation is minimised over this  
33 temperature range.

34  
35 Preferably during the consolidation, the temperature  
36 conditions include a stage where the temperature  
37 gradient falls at  $5^\circ\text{C min}^{-1}$  between  $1375^\circ\text{C}$  to  $650^\circ\text{C}$ .

1 Preferably, during the consolidation stage of at least  
2 one layer of said cladding layer, said first core layer  
3 and/or said second core layer overlying a doped  
4 substrate and/or another doped layer, the temperature  
5 conditions include a stage where the temperature remains  
6 above the softening temperature of the underlying  
7 substrate and/or other layer in its undoped state for at  
8 least 60 minutes.

9  
10 The present invention will be further illustrated by way  
11 of example, with reference to the accompanying drawings  
12 in which:-

13  
14 Fig 1 is a flow chart illustrating the fabrication steps  
15 of an optical channel waveguide according to a preferred  
16 embodiment of the invention;

17  
18 Figs 2A to 2D are schematic diagrams showing the  
19 formation of an optical channel waveguide according to a  
20 preferred embodiment of the invention;

21  
22 Fig 3 illustrates the variation of the refractive index  
23 of the dopants  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{GeO}_2$ ,  $\text{P}_2\text{O}_5$ ,  $\text{B}_2\text{O}_3$ , and F as a  
24 function of the dopant concentration;

25  
26 Fig 4 illustrates the variation in the coefficient of  
27 expansion of an  $\text{SiO}_2$  layer as the dopant concentration of  
28  $\text{GeO}_2$ ,  $\text{P}_2\text{O}_5$ ,  $\text{B}_2\text{O}_3$ , and  $\text{TiO}_2$  increases;

29  
30 Fig 5 illustrates the variation of the softening  
31 temperature of the dopant concentration of  $\text{GeO}_2$ ,  $\text{P}_2\text{O}_5$ ,  
32  $\text{B}_2\text{O}_3$ ;

33  
34 Fig 6A is a schematic illustration which shows the  
35 variation of the codopant concentration as a function of  
36 position in the core layer; and

37

1 Fig 6B is a schematic illustration which shows the  
2 variation of the softening temperature of the core as a  
3 function of position in the core layer.

4  
5 Referring to the drawings, Fig 1 illustrates the  
6 fabrication steps according to an embodiment of the  
7 invention of a method of forming an optical waveguide  
8 with a multi-layer core. Fig 1 illustrates the main  
9 steps of fabrication and is not intended to completely  
10 delimitate the fabrication process. Conventional,  
11 interim steps have been omitted.

12  
13 Referring to Figs. 2A to 2D, the method of fabricating  
14 an optical waveguide 1 with a multi-layer core is shown.

15  
16 Fig. 2A, shows an buffer layer 3, for example a buffer  
17 or under-cladding layer, is formed on top of a substrate  
18 2. In this example, the buffer layer 3 is silica ( $\text{SiO}_2$ )  
19 formed by thermally oxidising a silicon substrate.  
20 Alternatively, more than one buffer layer 3 may be  
21 formed by any suitable process, for example, depositing  
22 and consolidating a glass soot as described herein below  
23 in the description of the formation of the upper-  
24 cladding layer 8.

25  
26 Referring now to Fig. 2B, a first core layer 4 is formed  
27 on top of the buffer layer 3. The first core layer 4 is  
28 deposited using a suitable deposition process, for  
29 example, a flame hydrolysis deposition (FHD) process.  
30 Other suitable deposition processes include, for  
31 example, plasma enhanced chemical vapour deposition  
32 (PECVD) and low pressure chemical vapour deposition  
33 (LPCVD) or a combination of deposition processes.

34  
35 In the FHD process, a soot layer of fine, particulate  
36 glass material(s) is deposited on top of the buffer  
37 layer 3. If, for example, a  $6\mu\text{m}$  core layer is to be

ultimately formed, sufficient glass material is initially deposited to give rise to the formed first core layer 4 having a thickness of 5.5  $\mu\text{m}$ .

The glass material is typically silicon and/or germanium oxides, for example  $\text{SiO}_2$  and/or  $\text{GeO}_2$ . In the preferred embodiment of the invention, the glass material is doped during the deposition stage. Typical dopants, chosen for their effect on the thermal characteristics, refractive index and coefficient of expansion of the layer are selected quantities of, for example, boron, phosphorus, and/or titanium compounds ( $\text{B}_2\text{O}_3$ ,  $\text{P}_2\text{O}_5$ ,  $\text{TiO}_2$ ) *inter alia* other ion species.

The composition of the glass forming the first core layer 4 is selected to have a consolidation temperature close to approximately  $1360^\circ\text{C}$ , or close to the maximum possible.

Certain characteristics of the glass are enhanced by introducing heavier dopant species, such as other transition elements, rare earths and/or heavy metals, which may be introduced using specialised techniques, for example an aerosol doping technique such as disclosed in United Kingdom Patent Application No.9902476.2.

Still referring to Figs 1 and 2B, a second core layer 5 is formed on the first core layer 4. The second core layer 5 is deposited using any suitable deposition technique, for example FHD, on top of the first core layer 4. In one embodiment of the example, the second core layer has a much shallower depth than the first core layer as it is desirable to keep the glass material forming the second core layer 5 to a small fraction of the total core composition. It is sufficient to deposit sufficient material to form only a surface "skin" over

1 the underlying first core layer 4 when the second core  
2 layer 5 is consolidated and softened. In one embodiment  
3 of the invention, where a  $6\mu\text{m}$  deep core layer is being  
4 formed, the second core layer has a consolidated depth  
5 of  $0.5\ \mu\text{m}$ .

6  
7 The glass forming the second core layer 5 has a  
8 different composition from the first core layer 4. By  
9 varying, normally increasing, the dopant concentrations  
10 and/or suitably selecting the dopant species of the  
11 second core layer 5, the softening temperature  $T_{2s}$  of the  
12 second core layer 5 can be sufficiently reduced. The  
13 softening temperature of a layer is the temperature at  
14 which the viscosity of the consolidated layer is reduced  
15 sufficiently for the consolidated layer to begin to  
16 'flow', which, for example, can smooth out any surface  
17 irregularities of the layer. Reducing  $T_{2s}$  by selectively  
18 doping the constituent glass material forming the second  
19 core layer 5 ensures the second core layer 5 has already  
20 reached its consolidation temperature  $T_{2c}$  and further has  
21 reached its softening temperature  $T_{2s}$  as the underlying  
22 first core layer 4 is consolidating. The consolidation  
23 temperature  $T_{2c}$  and the softening temperature  $T_{2s}$  of the  
24 second core layer are thus both below the consolidation  
25 temperature  $T_{1c}$  of the first core layer 4. This results  
26 in the second core layer 5 beginning to flow to form a  
27 smooth surface during the consolidation phase.

28  
29 The glass material used to form the second core layer 5  
30 further produces the desired effect of, for example,  
31 matching the refractive index of the first core layer 4  
32 to the second core layer 5. Thus by heating both the  
33 first and second core layers 4,5, the second core layer  
34 5 will soften and flow as the first core layer  
35 consolidates which reduces the surface roughness at the  
36 interface between the two core layers 4, 5 as well as  
37 the topmost surface of the composite core layer 6.

1 It is desirable for the softening temperature of the  
2 second core layer to be in the temperature range over  
3 which the first core layer consolidates.

4  
5  
6 Referring now to the embodiment outlined in Fig. 1, the  
7 second core layer 5 is deposited before the first core  
8 layer 4 is consolidated. Alternatively, the second core  
9 layer 5 may be deposited when the first core layer 4 is  
10 partially consolidated. In the embodiment of the  
11 invention shown in Fig. 1, both core layers 4 and 5 are  
12 initially deposited by an FHD process and are fully  
13 consolidated together to form a composite core layer 6.  
14 Alternatively, each core layer 4,5 could be deposited  
15 and consolidated separately to form the composite core  
16 layer 6.

17  
18 Referring now to Fig. 2C, once the composite layer 6 has  
19 been formed, a waveguide core 7 is formed by using any  
20 suitable etching technique(s), for example  
21 photolithographic process(es) and dry etching, to remove  
22 unwanted portions of the core layers 4,5. The remaining  
23 composite core layer 6 forms the waveguide core 7 which  
24 is then embedded in an upper-cladding layer 8.

25  
26 Referring now to Fig. 2D, the upper-cladding layer 8 is  
27 formed by depositing a suitable glass material around  
28 the waveguide core 7 using any suitable deposition  
29 process, for example FHD, as described hereinbefore.  
30 The composition of the upper-cladding layer 8 may be  
31 varied by introducing dopants in order for the upper  
32 cladding layer 8 to possess certain desirable  
33 characteristics. For example, in the preferred  
34 embodiment of the invention the upper cladding layer 8  
35 has the same refractive index as the refractive index of  
36 the buffer layer 3, and has a consolidation temperature  
37  $T_{uc}$  which is lower than that of the softening

1 temperatures  $T_{1s}$  and  $T_{2s}$  of the first and second core  
2 layers 4,5. Additionally, the expansion coefficient of  
3 the upper cladding layer 8 should be similar to that of  
4 the substrate.

5  
6 Generally, to ensure that the consolidation of any one  
7 layer does not cause any thermal deformation of the  
8 underlying layer(s) and substrate 2, each layer of a  
9 waveguide possesses the desired characteristic that its  
10 consolidation temperature is less than the softening  
11 temperature of the previous layer. Alternatively, for  
12 example, buffer layers can be formed in between each  
13 layer of the waveguide to act as a thermal barrier.

14  
15 Each of the first and second core layers 4,5 is  
16 consolidated using a temperature cycle which includes a  
17 stage at a temperature significantly above the actual  
18 consolidation temperature. By subjecting the first and  
19 second core layers 4,5 to such an extreme temperature,  
20 the core layer with the lowest viscosity will flow so  
21 that it forms a relatively smooth and even surface. The  
22 high temperatures required to consolidate the composite  
23 core layer 6 may be achieved by known techniques, for  
24 example, passing a burner flame from a flame hydrolysis  
25 burner over the deposited soot layer or by placing the  
26 waveguide 1 in a suitable furnace.

27  
28 In one embodiment, to ensure that the uppermost surface  
29 of the core composite layer 6 is as smooth as possible,  
30 the second core layer 5 is heavily doped to reduce its  
31 consolidation temperature  $T_{2c}$  and softening temperature  
32  $T_{2s}$  to below the consolidation temperature  $T_{1c}$  of the  
33 first core layer 4. The general effect of the  
34 concentration of dopants in a layer with respect to the  
35 softening temperature is illustrated in Fig 5.

36  
37 Fig 5 indicates that the higher the concentration of

1 phosphorus, boron and germanium oxide in a layer, the  
2 lower the softening temperature. However, the presence  
3 of such dopants also affects the refractive index of a  
4 layer as is illustrated in Fig. 3. This illustrates  
5 that increasing the quantity of phosphorus and germanium  
6 oxide increases the refractive index, whereas the  
7 presence of boron oxide tends to reduce it.

8  
9 To ensure that the second core layer 5 has a minimal  
10 detrimental effect on the uniformity of the refractive  
11 index of the waveguide 7 formed from the composite core  
12 layer 6, the thickness of the second core layer 5 is  
13 less than the thickness of the first core layer 4. In  
14 the preferred embodiment of the invention, for a  
15 composite core layer 6 with a total thickness of 6  $\mu\text{m}$ ,  
16 the thickness of the first core layer 4 is 5.5  $\mu\text{m}$  and  
17 the thickness of the second core layer 5 is 0.5  $\mu\text{m}$ .  
18 In other preferred embodiments of the invention, the  
19 thickness of the second core layer 5 is around 10% of  
20 the total thickness of the composite core layer 6.

21  
22 The consolidation temperature of the first core layer 4  
23 is increased by selecting suitable dopant concentrations  
24 to ensure the consolidation temperature  $T_{1c}$  of the first  
25 core layer 4 exceeds the softening temperature  $T_{2s}$  of the  
26 second core layer 5. Thus by selecting suitable  
27 quantities of dopant in each of the core layers 4,5 it  
28 is possible to obtain the desired effect

$$T_{1c} > T_{2s} > T_{2c}.$$

29  
30  
31 In the preferred embodiment of the invention, the first  
32 core layer 4 has a composition which is selected to give  
33 a consolidation temperature  $T_{1c}$  near 1360°C. The  
34 composition of the second core layer 5 is such that the  
35 consolidation temperature  $T_{2c}$  and the softening  
36 temperature  $T_{2s}$  of the second core layer 5 are below the  
37 consolidation temperature  $T_{1c}$  of the first core layer 4.

1 For example, in one embodiment of the invention, the  
2 second core layer 5 is selectively doped with a higher  
3 concentration of  $\text{GeO}_2$  and  $\text{B}_2\text{O}_3$  so that its consolidation  
4 temperature  $T_{c2}$  is reduced to at least  $50^\circ\text{C}$  less than the  
5 consolidation temperature  $T_{1c}$  of the first core layer 4.  
6 Furthermore, the softening temperature of the second  
7 core layer is reduced to at least  $10^\circ\text{C}$  less than the  
8 consolidation temperature  $T_{1c}$  of the first core layer 4.

9  
10 The composition of the second core layer 5 is further  
11 selected so that its refractive index is substantially  
12 equal to the refractive index of the first core layer 4.

13  
14 Fig. 6A sketches the composite core layer 6 and dopant  
15 concentration levels in an embodiment of the invention.  
16 The area forming the second core layer 5 is shaded on  
17 the plot. The lower line represents the variation of  
18 the concentration of boron oxide ( $\text{B}_2\text{O}_3$ ), the upper line  
19 represents the variation of the concentration of  
20 germanium oxide ( $\text{GeO}_2$ ). The concentrations of boron  
21 oxide and germanium oxide increase in the second core  
22 layer 5 compared to their concentrations in the first  
23 core layer 4. This achieves a suitable reduction in the  
24 softening temperature  $T_{2s}$  of the second core layer 5, as  
25 Fig. 6B illustrates without radically affecting the  
26 overall refractive index of the composite core layer 6.

27  
28 When the composite core layer 6 is consolidated at the  
29 consolidation temperature of the first core layer 4, the  
30 first core layer 4 and the second core layer 5 are both  
31 fully consolidated. However,  $T_{1c}$  is greater than  $T_{2s}$ , and  
32 as the second core layer 5 is heated to above its  
33 softening temperature  $T_{2s}$ , its viscosity is sufficiently  
34 reduced for its uppermost surface to flow. This effect,  
35 the "surface skinning" of the second core layer 5, gives  
36 the composite core layer 6 a desirably low surface  
37 roughness itself and further, a low surface roughness to

1 the interface between the first and second core layers.  
2 Furthermore, the detrimental effects of the high  
3 concentrations of dopant required to reduce the  
4 softening temperature are mitigated as there is no need  
5 for high dopant concentrations to be present throughout  
6 the composite layer 6.

7  
8 It is desirable for the consolidation of the second core  
9 layer 5 not to occur prematurely, as this could result  
10 in gas being potentially trapped between the first and  
11 second core layers of the composite core layer 6. Gas  
12 may become trapped during premature consolidation as  
13 follows: the deposited soot particles initially form an  
14 open network with pores; as the pores close during the  
15 consolidation process, the layers become increasingly  
16 dense and gas pockets are expelled. If the pore network  
17 of the second core layer 5 is fully collapsed before the  
18 pore network of the first core layer 4 has collapsed,  
19 gas emitted from the first core layer 4 may be trapped  
20 beneath the second core layer 5.

21  
22 To prevent premature consolidation of the second core  
23 layer 5, the temperature range over which the composite  
24 core 6 is heated includes a typical consolidation ramp  
25 rate of  $5^{\circ}\text{C min}^{-1}$ . This removes the possibility of the  
26 second core layer prematurely consolidating and trapping  
27 gas bubbles. Other means to promote pore collapse may  
28 also be used, for example, He gas may be included during  
29 the consolidation phase to promote core collapse.

30  
31 In the preferred embodiment of the invention, the first  
32 core layer 4 may be formed with a refractive index of  
33 0.7% of the buffer layer 3 by using the following gas  
34 flows during the FHD process stage:

35  
36

First core layer			Second core layer	
Bubbler	Flow Rate		Bubbler	Flow Rate
Gas	(sccm)		Gas	(sccm)
SiCl <sub>4</sub>	150		SiCl <sub>4</sub>	150
GeCl <sub>4</sub>	101		GeCl <sub>4</sub>	156
BCl <sub>3</sub>	49		BCl <sub>3</sub>	65
Transport	Flow Rate		Transport	Flow Rate
Gases			Gases	
H <sub>2</sub> :O <sub>2</sub>	5 Lmin <sup>-1</sup> :7 Lmin <sup>-1</sup>		H <sub>2</sub> :O <sub>2</sub>	5 Lmin <sup>-1</sup> :7 Lmin <sup>-1</sup>

The above composition is purely illustrative. The invention seeks to provide a refractive index for the first core layer 4 which is substantially the same refractive index for the second core layer 5, the composition of both core layers 4,5 being such that index matching can be achieved without any substantial thermal deformation occurring to the first core layer 4 during the consolidation and/or fabrication of the second core layer 5. In this example, the composition of the material is selected to provide a refractive index difference of approximately 0.7% , with the second layer having substantially the same refractive index.

The temperature cycle for this embodiment is as follows during consolidation of the composite core layer 6:

650°C to 850°C	15°C min <sup>-1</sup>
850°C to 1375°C	5° min <sup>-1</sup>
1375°C to 650°C	-5° min <sup>-1</sup>

The core layer 6 remains at the peak temperature for 80 minutes in an helium oxygen atmosphere (0.6 L min<sup>-1</sup> He and 0.2 L min<sup>-1</sup> O<sub>2</sub>) before being cooled to 650°C at -5°C

1 min<sup>-1</sup>. Consolidation of the first layer occurs for T<sub>1c</sub>  
2 between 1200°C and 1375°C. Consolidation of the second  
3 layer occurs over a lower range: T<sub>2c</sub> between 1100°C and  
4 1365°C.

5  
6 While several embodiments of the present invention have  
7 been described and illustrated, it will be apparent to  
8 those skilled in the art once given this disclosure that  
9 various modifications, changes, improvements and  
10 variations may be made without departing from the spirit  
11 or scope of this invention.

12  
13 More than two core layers may be formed in the multi-  
14 layer core, and the composition of each core layer  
15 selected so that joint or separate consolidation can  
16 occur but so that the surface layer of the topmost core  
17 layer is subjected to skinning without the risk of  
18 thermal deformation of any of the underlying layers or  
19 any decrease in the overall uniformity and/or quality of  
20 the density/refractive index of the composite core.  
21 Accordingly, the composition of each core layer can be  
22 selected to achieve the aforementioned advantages.

23  
24 Any range given herein may be extended or altered  
25 without losing the effects sought, as will be apparent  
26 to the skilled person for an understanding of the  
27 teachings herein.

28

## 1 CLAIMS:

2

3 1. An optical waveguide (1) with a multi-layer  
4 waveguide core (7), the waveguide (1) comprising:

5 a substrate (2);

6 a waveguide core (7) formed on the substrate (2);

7 and

8 at least one upper cladding layer (8) embedding  
9 said waveguide core (7), the waveguide core (7) having  
10 a composite core layer (6) comprising:

11 a first core layer (4) with a softening temperature  
12  $T_{1s}$  formed on the substrate (2); and

13 at least one other core layer (5) formed on the  
14 first core layer (4), wherein the softening temperature  
15  $T_{2s}$  of at least one of said at least one other core  
16 layers (5) is less than the softening temperature  $T_{1s}$  of  
17 an underlying core layer (4,5).

18

19 2. An optical waveguide (1) as claimed in claim 1,  
20 wherein the softening temperature  $T_{2s}$  of at least one of  
21 said at least one other core layers (5) is at least 10°C  
22 less than the softening temperature  $T_{1s}$  of at least one  
23 underlying core layer (4,5).

24

25 3. An optical waveguide (1) as claimed in any  
26 preceding claim, wherein the softening temperature  $T_{2s}$  of  
27 at least one of said at least one other core layers (5)  
28 is substantially equal to or less than a consolidation  
29 temperature  $T_{1c}$  of at least one underlying core layer  
30 (4,5).

31

32 4. An optical waveguide (1) as claimed in any  
33 preceding claim, wherein said substrate (2) is a silicon  
34 wafer.

35

36 5. An optical waveguide (1) as claimed in Claim 4,  
37 wherein said substrate (2) further comprises at least

1 one buffer layer (3) formed thereon.

2

3 6. An optical waveguide (1) as claimed in claim 5,  
4 wherein at least one of said at least one buffer layer  
5 (3) is a thermally oxidised layer of the substrate (2).

6

7 7. An optical waveguide (1) as claimed in any one  
8 preceding claim, wherein at least one layer of said:  
9 first core layer (4), said at least one other core layer  
10 (5), and/or said at least one upper cladding layer (8)  
11 comprises silica and/or germanium oxide.

12

13 8. An optical waveguide (1) as claimed in any one  
14 preceding claim, wherein at least one layer of said:  
15 first core layer (4), said at least one other core layer  
16 (5), and/or said at least one upper cladding layer (8)  
17 is doped with at least one ion species taken from the  
18 group consisting of:

19 phosphorus, boron, titanium, tantalum, aluminium,  
20 lanthanum, niobium, zirconium and/or any other  
21 transition element.

22

23 9. An optical waveguide (1) as claimed in claim 4,  
24 wherein said at least one silica and/or germanium oxide  
25 layer is doped with at least one species taken from the  
26 group consisting of:

27 a transition element, a rare earth ion species  
28 and/or a heavy metal ion species.

29

30 10. An optical waveguide (1) as claimed in any  
31 preceding claim wherein the thickness of first core  
32 layer (4) is greater than the thickness of said at least  
33 one other core layer (5).

34

35 11. An optical waveguide (1) as claimed in claim 8,  
36 wherein the thickness of the first core layer (4) is  
37 the major portion of the thickness of the composite core

1 layer (6).

2

3 12. A method of fabricating an optical waveguide (1)  
4 with a waveguide core (7) comprising the steps of:

5 forming a substrate (2);

6 forming a composite core layer (6) on said  
7 substrate;

8 forming a waveguide core (7) from said composite  
9 core layer (6); and

10 forming at least one upper-cladding layer (8) to  
11 embed said core waveguide (7), wherein the formation of  
12 the composite core layer (6) is characterised by:

13 forming a first core layer (4) with a softening  
14 temperature  $T_{1s}$  on the substrate (2); and

15 forming at least one other core layer (5) on the  
16 first core layer (4), wherein the softening temperature  
17  $T_{2s}$  of at least one of said at least one other core layer  
18 (5) is substantially less than the softening temperature  
19  $T_{1s}$  of at least one underlying core layer (4,5).

20

21 13. A method as claimed in Claim 12, wherein the  
22 softening temperature  $T_{2s}$  of at least one of said at  
23 least one other core layer (5) is at least 10°C less  
24 than the softening temperature  $T_{1s}$  of at least one  
25 underlying core layer (4,5).

26

27 14. A method as claimed in either Claim 12 or Claim 13,  
28 wherein the softening temperature  $T_{2s}$  of at least one of  
29 said at least one other core layer (5) is substantially  
30 equal to or less than a consolidation temperature  $T_{1c}$  of  
31 at least one underlying core layer (4,5).

32

33 15. A method as claimed in any one of claims 12 to 14,  
34 wherein at the softening temperature  $T_{2s}$  of the said at  
35 least one other core layer (5), the viscosity of the  
36 said at least one other core layer (5) is sufficiently  
37 reduced to lessen surface irregularities in said at

1 least one other core layer (5).

2

3 16. A method as claimed in claim 12 to 15, wherein said  
4 step of forming a substrate (2) includes the formation  
5 of at least one buffer layer (3) on said substrate (2).

6

7 17. A method as claimed in any one of claims 12 to 16,  
8 wherein the formation of at least one of: said at least  
9 buffer layer (2), said first core layer (4), said at  
10 least one other core layer (5), and said upper cladding  
11 layer (8) comprises the steps of:

12 depositing a soot layer of fine particulate  
13 material;

14 consolidating said deposited soot layer.

15

16 18. A method as claimed in any one of claims 12 to 17,  
17 wherein said soot deposition is by a flame hydrolysis  
18 deposition process, and/or any other planar soot  
19 deposition technique or combination of soot depositing  
20 techniques and non-soot depositing techniques.

21

22 19. A method as claimed in claim 17 or claim 18,  
23 wherein said consolidation is by heating with a flame  
24 hydrolysis burner and/or in a furnace.

25

26 20. A method as claimed in claim 19, wherein the  
27 formation of at least one of: said at least buffer layer  
28 (2), said first core layer (4), said at least one other  
29 core layer (5), and said upper cladding layer (8)  
30 comprises the steps of:

31 depositing said layers of material by means of a  
32 plasma enhanced chemical vapour deposition process, a  
33 low pressure chemical vapour deposition process and/or  
34 any other planar deposition technique or combination of  
35 deposition techniques;

36 subjecting the deposited layer to a temperature  
37 controlled environment such that said deposited layer is

1 sintered.

2

3 21. A method as claimed in any one of claims 12 to 20,  
4 wherein the composition of at least one layer of said:  
5 first core layer (4), at least one other core layer (5),  
6 and/or said at least one upper cladding layer (8)  
7 includes silica and/or germanium oxide.

8

9 22. A method as claimed in any one of claims 12 to 21,  
10 wherein at least one layer of said: first core layer  
11 (4), said at least one other core layer (5), and/or said  
12 at least one upper cladding layer (8) is doped with at  
13 least one ion species taken from the group consisting  
14 of:

15 phosphorus, boron, titanium, tantalum, aluminium,  
16 lanthanum, niobium, zirconium and/or any other  
17 transition element.

18

19 23. A method as claimed in claim 22, wherein said at  
20 least one silica and/or germanium oxide layer is doped  
21 at least one ion species taken from the group consisting  
22 of:

23 a transition element, a rare earth ion species  
24 and/or a heavy metal ion species.

25

26 24. A method as claimed in any one of claims 19 to 23,  
27 wherein the quantities of dopant are selected to form a  
28 waveguide with a refractive index difference of between  
29 0.2-2% with respect to the buffer.

30

31 25. A method as claimed in any one of claims 19 to 24,  
32 wherein the lower core layer is  $\text{SiO}_2$  co-doped with a  
33 Germanium and/or Boron and/or Phosphorus ion species.

34

35 26. A method as claimed in any one of claims 19 to 24,  
36 wherein the upper core layer is  $\text{SiO}_2$  co-doped with a  
37 Germanium and/or a Boron and/or Phosphorus ion species.

1 27. A method as claimed in any one of Claims 19 to 26,  
2 wherein the softening temperature ( $T_{2s}$ ) of the said at  
3 least one other core layer (5) is at least  $10^{\circ}\text{C}$  less  
4 than the consolidating temperature ( $T_{1c}$ ) of said first  
5 core layer (4).

6  
7 28. A method as claimed in any one of Claims 19 to 27,  
8 wherein the consolidation temperature ( $T_{1c}$ ) of said first  
9 core layer (4) is in the range  $1200^{\circ}\text{C}$ - $1375^{\circ}\text{C}$ .

10  
11 29. A method as claimed in any one of Claims 19 to 28,  
12 wherein in which the consolidation temperature  $T_{2c}$  of the  
13 second core layer is between  $1100^{\circ}\text{C}$  to  $1365^{\circ}\text{C}$ .

14  
15 30. A method as claimed in any one of claims 12 to 29,  
16 wherein the composition and concentration of dopants in  
17 any one lower layer and/or substrate is selected to  
18 control the degree of softness exhibited by any  
19 overlying layer at a predetermined temperature.

20  
21 31. A method as claimed in claim 19, wherein during the  
22 consolidation, the temperature conditions include a  
23 stage where the temperature gradient rises at  $15^{\circ}\text{C min}^{-1}$   
24 between  $650^{\circ}\text{C}$  to  $850^{\circ}\text{C}$ .

25  
26 31. A method as claimed in claim 19 or claim 30,  
27 wherein during the consolidation, the temperature  
28 conditions include a stage where the temperature  
29 gradient rises at  $5^{\circ}\text{C min}^{-1}$  between  $850^{\circ}\text{C}$  to  $1375^{\circ}\text{C}$ , and  
30 the dopant concentrations are selectively controlled so  
31 that thermal deformation is minimised over this  
32 temperature range.

33  
34 33. A method as claimed in any one of claims 31 to 32,  
35 wherein during the consolidation, the temperature  
36 conditions include a stage where the temperature  
37 gradient falls at  $5^{\circ}\text{C min}^{-1}$  between  $1375^{\circ}\text{C}$  to  $650^{\circ}\text{C}$ .

1     34. A method as claimed in any one of claims 31 to 33,  
2     wherein during the consolidation stage of at least one  
3     of said cladding layer, said first core layer and/or  
4     said second core layer overlying a doped substrate  
5     and/or another layer, the temperature conditions include  
6     a stage where the temperature remains above the  
7     softening temperature of the underlying substrate and/or  
8     other layer in its undoped state for at least 80  
9     minutes.

10

11     35. An optical waveguide (1) with a multi-layer core  
12     (6) as described substantially herein and with reference  
13     to the accompanying Figure 2 of the drawings.

14

15     35. A method of fabricating an optical waveguide (1)  
16     with a composite core as described substantially herein  
17     and with reference to the accompanying Figure 1 of the  
18     drawings.



Application No: GB 9923598.8  
Claims searched: 1-35

Examiner: Meredith Reynolds  
Date of search: 23 February 2000

## Patents Act 1977 Search Report under Section 17

### Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:  
UK CI (Ed.R): G2J (JGDA)  
Int CI (Ed.7): G02B 6/10.6/12  
Other:

### Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
X	US 5563979 (Lucent)(Figs 1, 4, Cols 3-7)	1,4,7-11 at least
X	US 5416884 (Sharp)(Figs 2-5, Cols 3-6)	1 at least
X	US 4929302 (Energie Atomique)(Figs 8-10, Cols 4-6)	1,4-8, 12 at least
X	US 4988156 (Mitsubishi)(Figs 1,3 and Cols 2-3)	1,7-8,12 at least

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.